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Pseudo-three-dimensional numerical model and investigation of multi-cluster fracturing within a stage in a horizontal well

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ABSTRACT

Multi-cluster fracturing and horizontal drilling are the key techniques used to exploit unconventional reservoirs. However, field production has revealed that certain perforation clusters are invalid. In order to find the most effective approaches to improve the uniformity of multiple-fracture growth, a pseudo-3D multi-cluster fracturing model is established in this study. In our model, complex in-situ stress distributions are considered and the stress interactions between fractures are calculated using the displacement discontinuity method (DDM). Fluid dynamic flow distributions into different clusters are calculated using Kirchhoff's second law. Fracture height and length extension velocities are determined based on the fracture edge energy release rate. The effectiveness of our model is verified by comparing the single fracture extension results obtained by our model to those obtained by a semi-analytical model. Based on our numerical model, possible approaches to promoting the uniform growth of multiple fractures are discussed. The results indicate that adjusting spacing is an inefficient method to promote multiple-fracture uniform growth under the condition of four clusters fracturing within a stage. However, regulating perforation friction, reducing fracturing fluid viscosity, and increasing injection rate are useful ways to improve the uniformity of multiple-fracture propagation.

1. Introduction

Large deposits of unconventional gas resources can be found worldwide; the porosity and permeability of unconventional reservoirs are extremely low (Li et al., 2017). Multistage hydraulic fracturing and horizontal drilling are the key techniques used to exploit such reservoirs (Zhang et al., 2017; S. Kanaun, 2017). However, field production has revealed that certain perforation clusters do not contribute to production (Camron, 2011). In other words, certain clusters are invalid. Additionally, Wheaton et al. (2014) provided data from a distributed acoustic sensor indicating that the two interior perforation clusters are invalid in the case of four-cluster fracturing. Therefore, it is necessary to establish a multiple-fracture propagation model to predict fracture trajectory and shape.

The first pseudo-3D fracture extension model was proposed by Simonson et al. (1978), who adopted the static stress intensity factor as a criterion for fracture extension in the vertical direction. Based on Simonson's model, Palmer and Carroll (1983a, 1983b) established the famous Palmer's model. However, their model is only suitable for simulating single fracture extension.

There have been numerous studies on multiple-fracture propagation in horizontal wells. These studies have indicated that multiple-fracture uniform growth can be accomplished by optimizing stimulation treatments. For example, Peirce and Bunger (2015) developed a 3D full coupling parallel-planar hydraulic fracture model to study the approaches used to reduce the stress shadowing effect. Their research indicated that adjusting cluster spacing can promote multiple-fracture uniform propagation.

Guo et al. (2015) established a 3D multiple-fracture growth model based on the ABAQUS finite element commercial software to simulate multi-cluster staged fracturing. They also proposed a cluster space optimization method that considers fracture geometry and the induced stress fields between fractures. However, their model assumes that fractures propagate along straight lines and does not consider the fluid dynamic flow distributions into different clusters. Sun et al. (2015) also developed a 3D multi-cluster fracturing model based on ABAQUS. Their study indicated that cluster spacing and net pressure are two critical factors for the effective implementation of multi-cluster fracturing. Sobhaniaragh et al. (2016) adopted the ABAQUS software to establish a 3D non-planar multistage hydraulic fracturing model to study multiple-fracture propagation in quasi-brittle shale multi-layer environments. Because the ABAQUS finite

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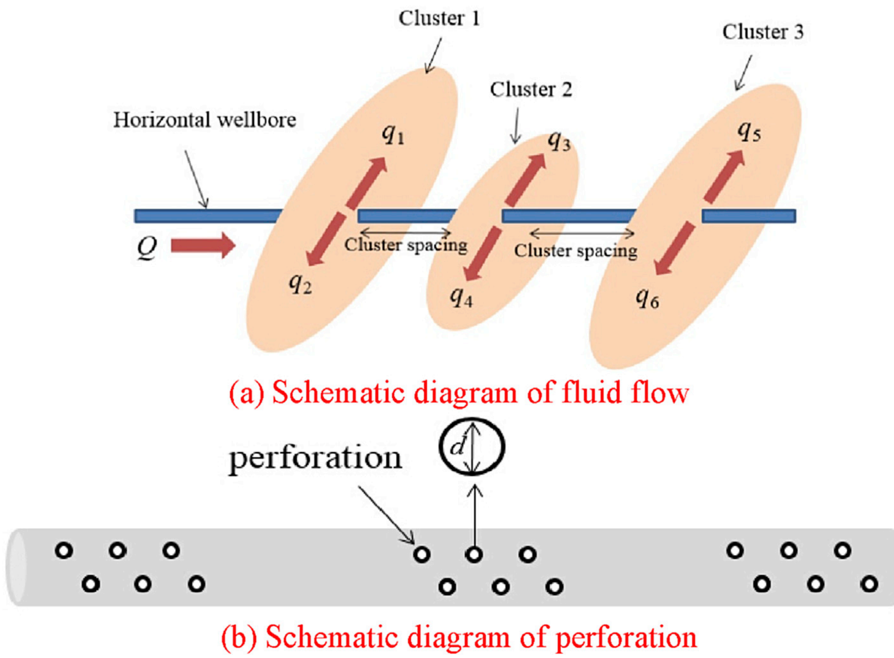

Fig. 1. Schematic of multi-cluster fracturing within a stage.

element commercial software can clearly describe any point mechanical properties of a calculation area, it has advantages for simulating fracture propagation in heterogeneous mediums. However, it requires enormous computing power. Another disadvantage of ABAQUS is that it cannot consider the influences of perforation friction and wellbore friction, meaning the fluid flow rate into each cluster is assumed to be constant.

In order to reduce the number of calculations required, some multi-cluster fracturing models have been established based on the displacement discontinuity method (DDM). The DDM was first proposed by Crouch (1976) and works by discretizing a discontinuity surface into a large number of fracture elements and then considering stress or displacement boundaries to establish algebraic equations. (Olson, 2008; Wu and Olson, 2015a, 2015b, 2015c) established several 2D multiple-fracture propagation models that simultaneously consider the stress shadowing effect, flow resistance from wellbore friction, perforation friction, fracture friction, and fracturing fluid leak-off. Their studies indicated that adjusting perforation friction or fracture spacing can promote multiple-fracture uniform propagation. (Zhao et al., 2016a, 2017) coupled the elastic deformation of rocks with fluid flows in perforation tunnels and fractures to establish a 3D multiple-fracture propagation model for horizontal wells. In their model, a method for coupling the asymptotic solutions of viscous regimes is used to calculate fracture tip locations. However, they did not consider the influence of wellbore friction. Based on Wu's studies, Li et al. (2017) also developed a simultaneous 2D multiple-fracture propagation model where the multiple-fracture propagation rate was determined based on the fracture tip energy release rate in their model.

In this study, our goal is to develop a new pseudo-3D multi-cluster fracturing model and investigate stimulation treatments to promote multiple-fracture uniform growth. In our model, we simultaneously consider the complex distributions of in-situ stresses, stress interactions between fractures, fluid dynamic flow distributions into different fractures, and fracturing fluid leak-off. Additionally, fracture height and length growth velocities are calculated according to the energy release rate of the fracture edge. Fracture length and height are obtained via summation of the fracture length and height extension lengths in each step. This is different from previous pseudo-3D models (Palmer and Carroll, 1983a; Zhao et al., 2016a, 2017) where fracture height was only a function of net pressure and fracture toughness. Using our model, we study various impact factors for multiple-fracture uniform growth. Finally, we propose three approaches to promote multiple-fracture uniform growth: adjusting perforation friction, reducing fracturing fluid viscosity, and increasing injection rate.

2. Physical model

The physical model for multi-cluster fracturing within a stage is illustrated in Fig. 1. Multi-cluster fracturing is a complex problem that combines six processes: (1) fracturing fluid flow in the wellbore; (2) fracturing fluid flow in the perforation tunnel; (3) fracturing fluid flow in the hydraulic fracture; (4) fracturing fluid flow from the hydraulic fracture wall to the formation; (5) formation rock deformation caused by the joint actions of fluid pressure, in-situ stress, and interference stress; and (6) hydraulic fracture propagation. Therefore, we make several assumptions to reduce computational complexity: (1) rock mechanical properties are linearly elastic and homogeneous, (2) fracturing fluid flow from the hydraulic fracture wall to the formation follows the Carter model, (3) fracturing fluid is incompressible, and (4) the effect of natural fractures on hydraulic fracture extension is negligible.

3. Mathematical model

3.1. Fracturing fluid flow model

In the process of multi-cluster fracturing within a stage, the flow

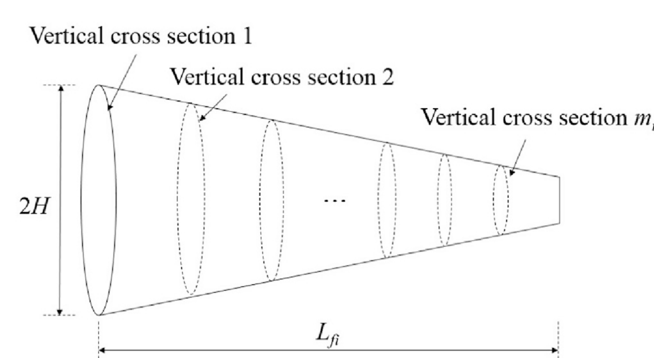

Fig. 2. Schematic of a discrete 3D fracture.